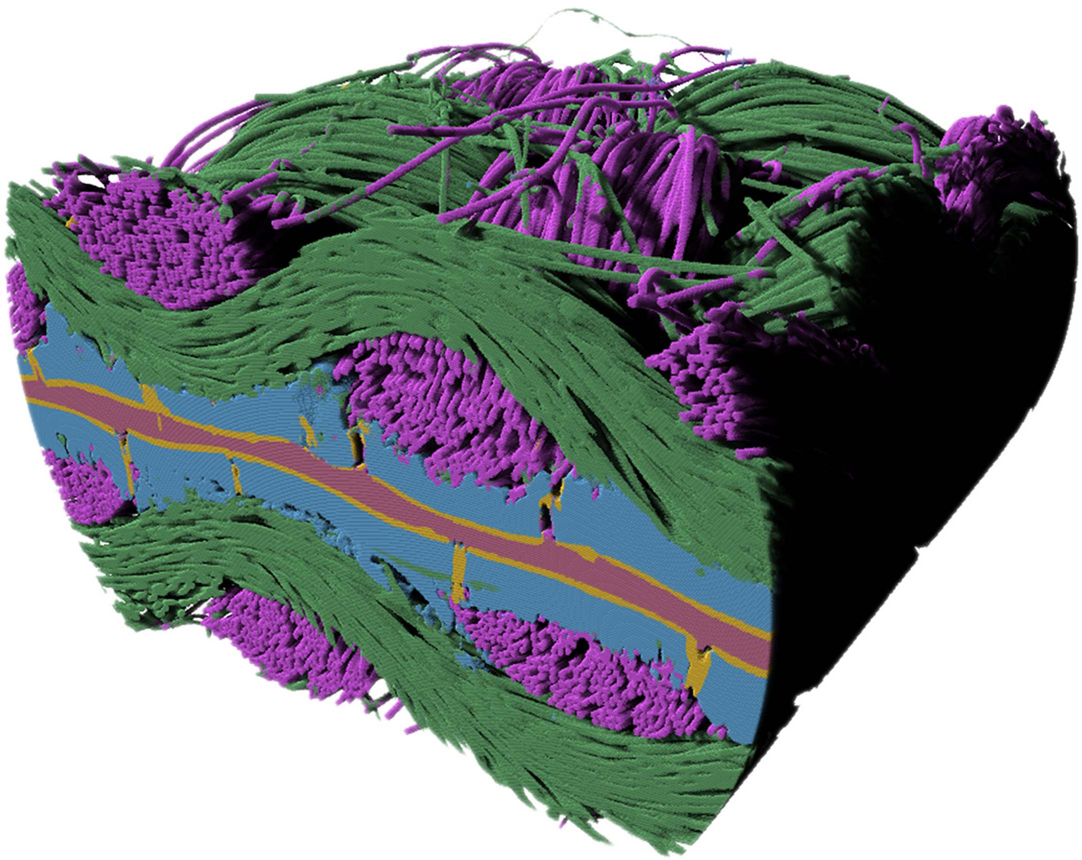
Technical Note

Expanding the Boundaries of 3D X-ray Imaging

ZEISS Xradia 515 Versa



Seeing beyond

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X-ray imaging has captured our imagination since the discovery and identification of X-rays by Wilhelm Röntgen in 1895. Two-dimensional X-ray imaging (radiography) has been in use ever since for applications ranging from medicine and industrial inspection to airport security. With the advent of the computed tomography (CT) method, three-dimensional X-ray imaging has further expanded the power of X-ray imaging to enable virtually slicing open an object and visualizing the interior without physically cutting the object of interest. This capability has similarly found widespread application in medicine, scientific research, and industrial inspection, and earned its inventors the 1979 Nobel Prize in Medicine. The advancements of modern computing infrastructures and data handling capabilities have significantly broadened the availability, use, and quantitative power of this technique. Meanwhile, advancements in X-ray source technologies to generate micrometer-sized illumination spots have allowed for increasingly high-resolution images to be obtained with this method – micro-computed tomography or microCT – enabling researchers to non-destructively look inside objects with high precision.

X-ray Microscopy

Beyond microCT, technological advancements have given rise to the development of so-called X-ray microscopy (XRM) with unique capabilities and higher resolution than that achieved with microCT. Originally developed at synchrotron beamlines where scintillator materials (to convert the X-rays into visible light) were coupled with traditional light microscope objectives, the technology was adapted to the laboratory in the mid-2000s and has evolved into the cutting edge family of ZEISS Xradia Versa X-ray microscopes. To understand what separates XRM from traditional microCT, we can look at a relatable example of imaging the interior of an apple.

In the standard microCT setup shown in Figure 1, the sample is positioned between a micro-focus X-ray source and a relatively large flat panel X-ray detector. The cone shape of the X-ray beam magnifies the transmission image onto the detector – a process known as geometric magnification. Moving the sample closer to the source increases magnification, while moving the sample closer to the detector results in less magnification and an image with a wider field of view.

While powerful in its simplicity, this method encounters limitations for higher resolution imaging. For instance, in our example of the apple, if high resolution images of a seed are required, the apple should be moved as close as possible to the X-ray source. However, at some point the magnification cannot be increased because of the size of the apple. To get the apple seeds closer to the X-ray source for higher resolution imaging, the apple must be cut open, the seeds removed, and mounted and imaged separately from the apple.

While cutting open an apple to image the seeds at higher resolution may be acceptable, for many applications and sample types you may not want or be able to cut open the sample to remove an internal portion for higher resolution imaging. A prime example of this is the field of battery research. Batteries are self-contained devices where performance is strongly dictated by the material arrangements within, but opening a battery destroys the functionality of the device, risks disturbing the intricate internal structures, and poses significant health and safety hazards to the researcher.

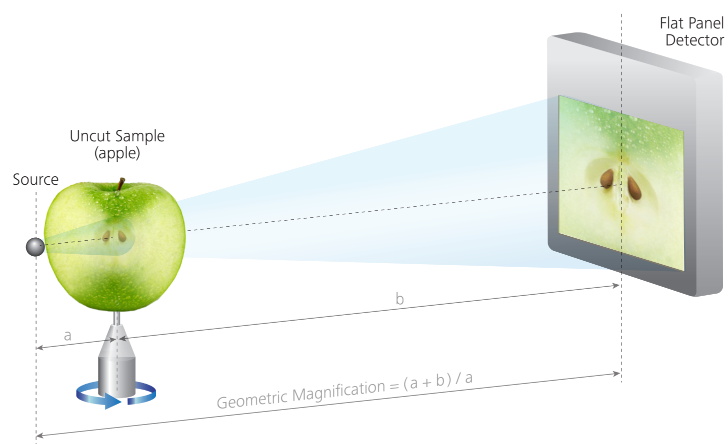


Figure 1 *Standard microCT imaging configuration with a micro-focus X-ray source, sample, and a relatively large pixelated flat panel X-ray detector.*

XRM breaks this barrier between resolution and sample size by introducing a two-stage magnification process as illustrated in Figure 2. After the geometric magnification stage, the transmitted X-rays are converted to visible light by a scintillator and are magnified by ZEISS proprietary optics in a second optical magnification step. By changing the optical magnification, this two-stage magnification allows for very high-resolution images of interior sample structures (here, the apple seed) to be collected without cutting the sample – a capability known as Resolution at a Distance (RaaD). RaaD is an extremely powerful capability that allows you to:

- Avoid destructive sample preparation steps such as serial sectioning
- Reveal the internal structure of objects at sub-micron resolution
- Collect high resolution images from diverse sample types and sizes
- Investigate microstructures under changing conditions and over time (such as *in situ*)
- Seamlessly move from overview scan to sub-micron details without the need for cutting, re-fixturing, or otherwise manipulating the sample

ZEISS Xradia Versa X-ray microscopes contain multiple sets of optics to provide optimized resolution and contrast capabilities across the full range of sample sizes from sub-millimeter up to 300 millimeters in diameter.

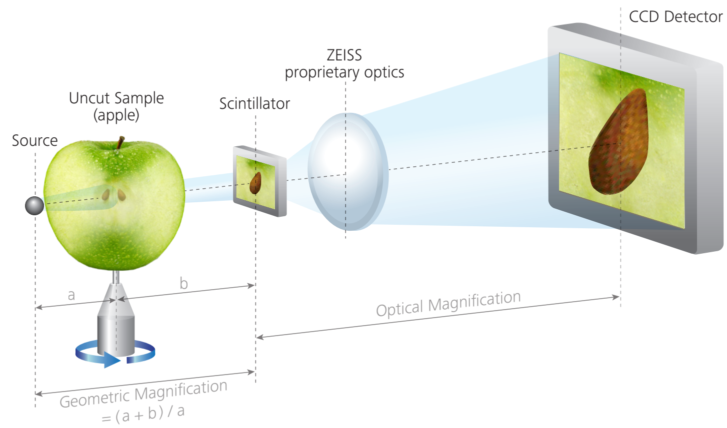


Figure 2 *X-ray microscope imaging configuration found in ZEISS Xradia Versa with two-stage magnification to enable Resolution at a Distance (RaaD). In addition to geometric magnification, ZIESS proprietary optics magnify the visible light image formed at the scintillator onto the CCD detector.*

Figure 3 shows an example of imaging a pouch cell battery, such as that found in popular commercial smart watches, using ZEISS Xradia Versa. RaaD, enabled by the range of available detectors found within the instrument, allows for high contrast overview imaging of the full battery with the 0.4X detector as well as high-resolution imaging of the internal particles that make up the individual layers of the battery anode and cathode using the 4X and 20X detectors.

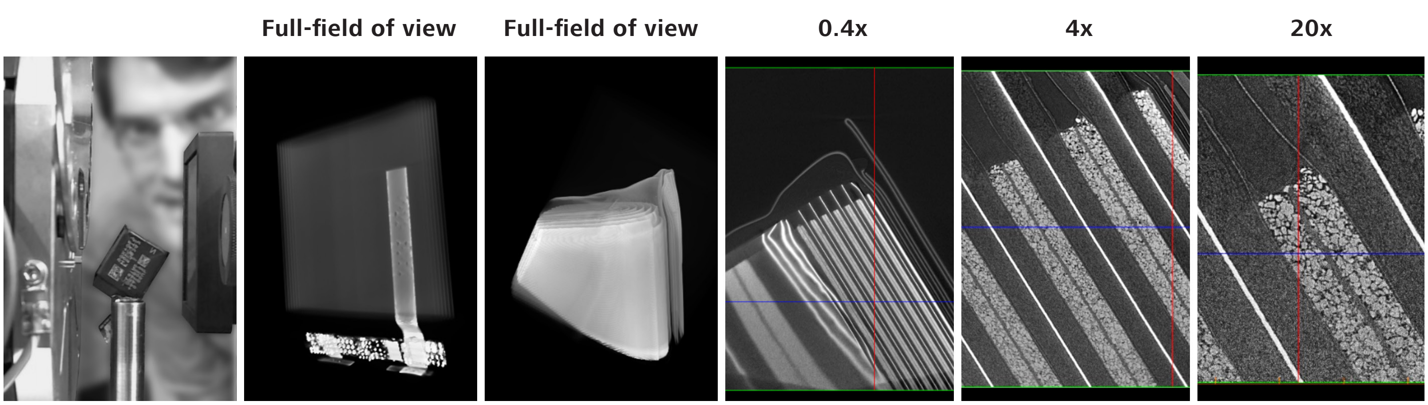
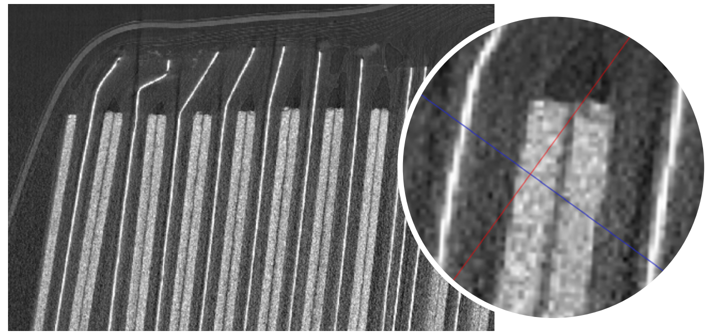


Figure 3 *XRM imaging of a commercial smart watch pouch cell battery. High-contrast overview imaging with the 0.4X detector allows for internal regions of interest to be identified for further high-resolution imaging with the 4X and 20X detectors.*

This allows researchers to examine the detailed internal microstructures of the battery in its assembled and functional state and makes possible studies of battery aging processes as the microstructures evolve with extended cycling.

In comparison, traditional microCT imaging cannot achieve the same level of magnification as XRM, as shown in Figure 4. The anode and cathode layers are visible, but their internal microstructure cannot be resolved, significantly limiting the information that can be obtained with microCT. This idea is illustrated in more detail in Figure 5 where achievable resolution is plotted versus source-to-sample working distance (similar to sample radius) for both XRM and microCT. As working distance or sample size increase, the achievable resolution for microCT drops steeply, while XRM maintains high-resolution imaging capability across a broad range of working distances and sample sizes.

Traditional X-ray microCT



ZEISS Xradia Versa

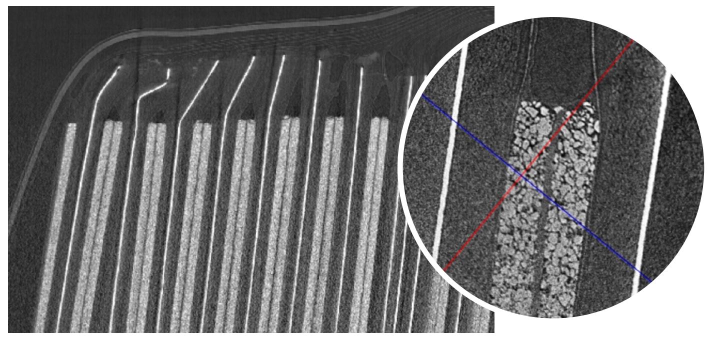


Figure 4 *Comparison between detail achievable with microCT and XRM for a commercial smart watch battery.*

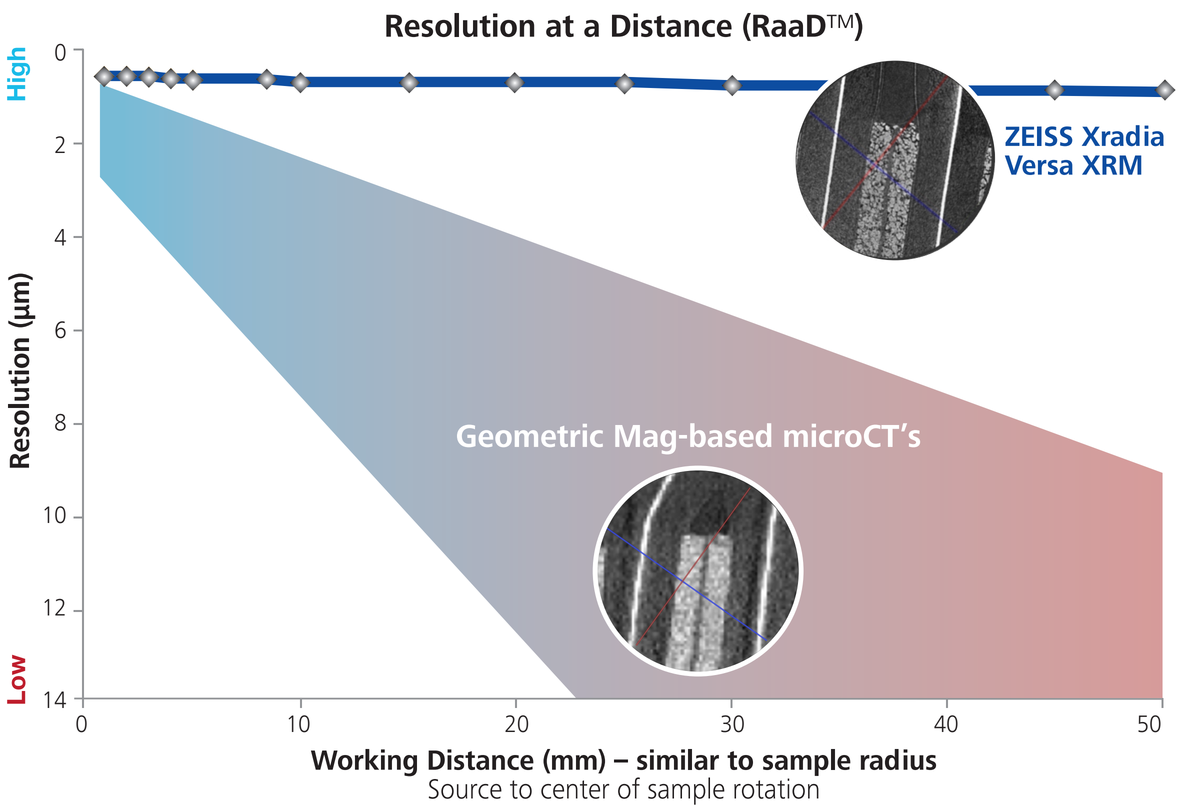
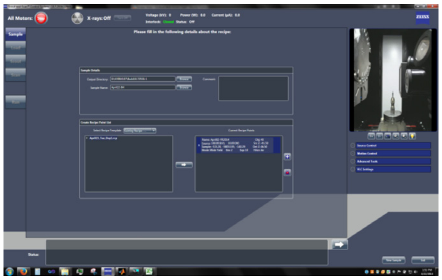


Figure 5 *Achievable spatial resolution versus source to sample working distance plotted for both XRM and geometric magnification-based microCT instruments. XRM maintains high resolution imaging capabilities across a wide range of sample sizes while the achievable resolution of microCT drops steeply as sample size increases.*

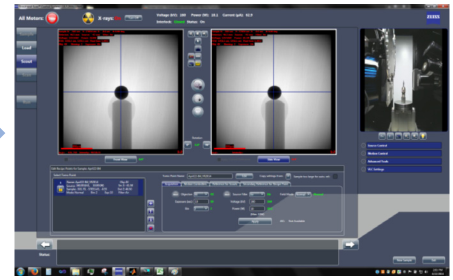
Intuitive, easy-to-use workflow interface

1) Enter Sample Details

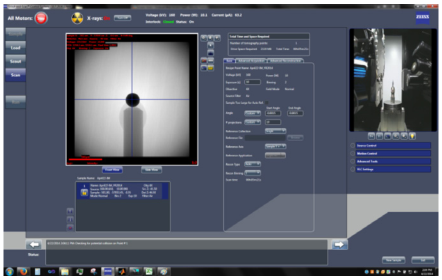


2) Load and Center Sample

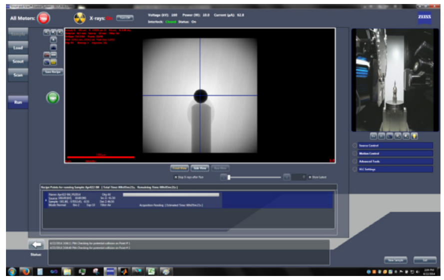
3) Position Region of Interest



4) Set-up Exposure Parameters



5) Run and Monitor Imaging



ZEISS Xradia Versa now with Python API

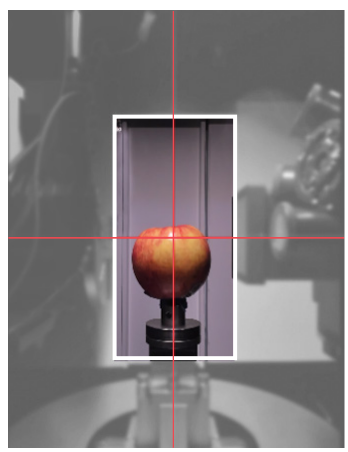
For scripting "unusual" acquisition, unique scanning strategies, accessing metadata and instrument states, advanced and automated *in situ* experiments

Figure 6 *The Scout-and-Scan Control System allows users to quickly and easily set up ZEISS Xradia Versa X-ray microscopes using an intuitive, workflow-based approach. The newly added Python API allows for easy extensibility and advanced access to microscope functions for complex experiments.*

Putting RaaD to Work – ZEISS Xradia 515 Versa

RaaD is at the core of ZEISS Xradia Versa X-ray microscopes, and ZEISS Xradia 515 Versa embodies this technology as the workhorse XRM for your research. With resolution down to 500 nm true spatial resolution with both absorption and phase contrast capabilities, ZEISS Xradia 515 Versa is a class-leading XRM with unmatched non-destructive 3D imaging capabilities. It builds on the proven reputation of ZEISS Xradia 5XX-series instruments, combining the stability and versatility of the ZEISS Xradia platform with state-of-the-art resolution capabilities and the newest software and usability improvements that come from years of X-ray microscope development. The intuitive, workflow-based ZEISS Scout-and-Scan control system, Figure 6, that powers all ZEISS Xradia instruments now includes ZEISS SmartShield automated protection system, Figure 7, to help users confidently position their sample and instrument components. Additionally, a new Python API expands instrument capabilities and gives users access to microscope operation and data handling through custom written external scripts and programs, enabling a new class of automation and experiment setup for applications such as *in situ* experiments.

Sample



Sample Envelope

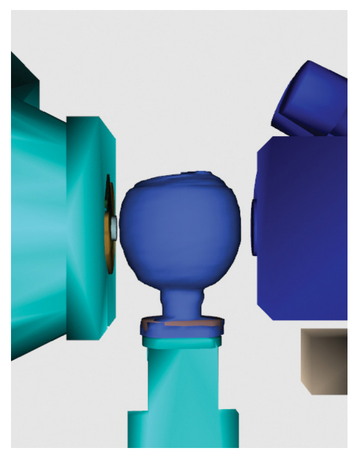


Figure 7 *ZEISS SmartShield protection system provides an additional layer of protection and allows users to set up ZEISS Xradia Versa X-ray microscopes with confidence.*

Latest Innovations in XRM – 6XX Series Xradia Versa

While RaaD and the ZEISS Xradia 5XX Versa X-ray microscope series broke through the technological barrier tying resolution to sample size, recent advancements have allowed the latest ZEISS Xradia 6XX Versa X-ray microscopes to build on these capabilities and break through another barrier – that tying resolution to throughput or scan speed. In traditional microCT, resolution and scan speed are linked by the X-ray spot size produced by the source. As illustrated in Figure 8, high throughput applications require high power, which increases the spot size. Conversely, high resolution applications of microCT require a very small spot size that can only be produced at low power and, as a result, low throughput.

Thus, traditional microCT users must decide between slow, high resolution imaging or faster, low resolution imaging. XRM architecture breaks free from this dependency, and ZEISS Xradia 6XX Versa X-ray microscopes deliver scan speeds up to twice as fast as those achievable with ZEISS Xradia 5XX Versa instruments while maintaining the leading high-resolution performance for which ZEISS Xradia Versa is known. This breakthrough is achieved with innovations in high power (25 W) X-ray source technology, improved thermal management and source control system, and enhanced detector capabilities.

In practice, this capability can be used in a variety of ways. For example, industrial failure analysis (FA) labs and/or academic core facilities can image more samples or parts per day to maximize service revenue and/or accommodate more users. Complex *in situ* imaging experiments can include more test points, increasing the accuracy and success rate of the experiment.

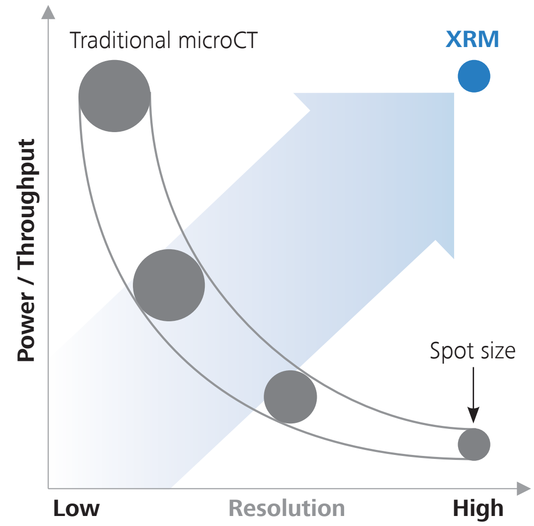


Figure 8 *Comparison between XRM and microCT for the relationship between X-ray source power, or throughput, and instrument resolution. While for microCT one must choose between high throughput or high resolution, ZEISS Xradia 6XX Versa XRM break that boundary and enable improved throughput while maintaining leading high-resolution capabilities.*

The increased X-ray flux can also be used to improve image quality by allowing more signal to be collected for an equivalent scan time as compared to instruments such as ZEISS Xradia 5XX Versa.

Figure 9 shows a range of applications that can be addressed, and associated throughput improvements brought by ZEISS Xradia 6XX Versa.

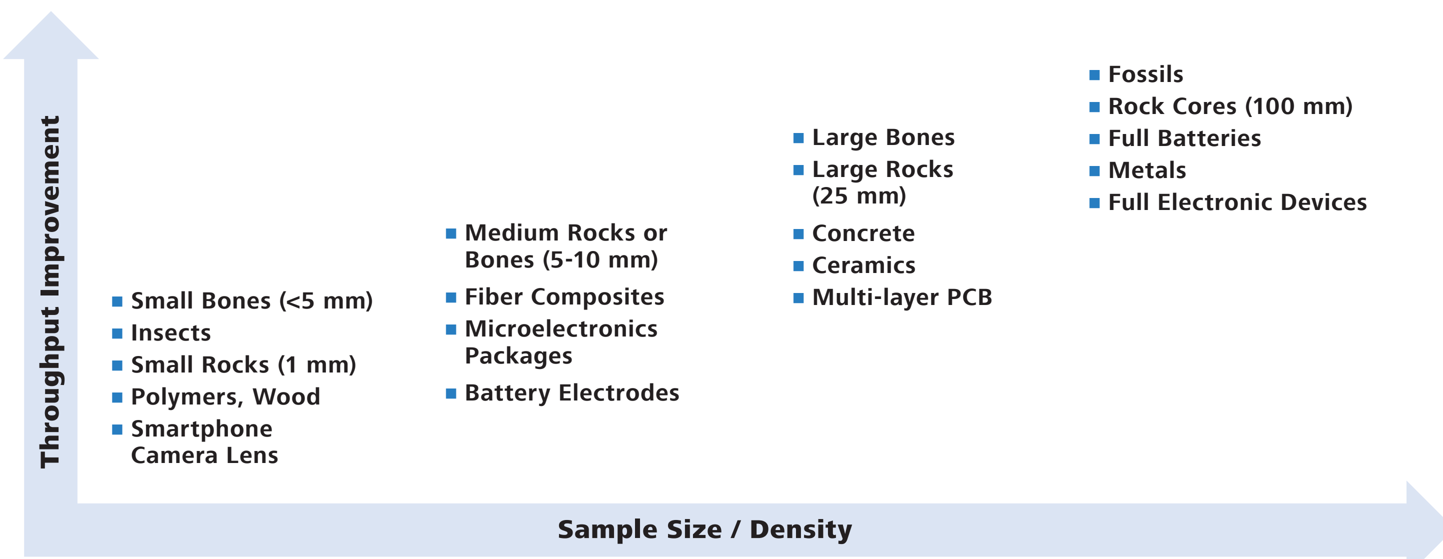


Figure 9 *Throughput improvments delivered by the next-generation XRM technology of ZEISS Xradia 6XX Versa X-ray microscopes for a variety of sample types and sizes.*

In addition to these dramatic throughput improvements, ZEISS Xradia 6XX Versa deliver several other next-generation enhancements. Increased reliability by design brings down the cost of ownership and maximizes instrument uptime. Improved operator efficiency, thanks to instant source activation, allows for sample runs to be set up and optimized faster to reduce valuable operator time. ZEISS Xradia 6XX Versa instruments also come with dual-GPU workstations enabling faster high-compute 3D reconstructions and thereby improving the overall time to results. For critical areas such as in academic core facilities and industrial FA labs, this all means that the instrument can be more productive, return high quality results more reliably, and provide maximum return on investment.

Summary

Since its invention, X-ray imaging has enabled significant advances in medicine, science and technology. What began as a two-dimensional technique evolved into the three-dimensional imaging technique of X-ray computed tomography, or CT, and led the way to higher resolution capabilities via microCT. The advent of Xradia X-ray microscope architecture brought breakthrough Resolution at a Distance (RaaD) capabilities and advances in contrast optimization. Finally, recent advances in XRM technology have enabled much faster imaging without compromising resolution. ZEISS Xradia X-ray microscopes uniquely deliver these capabilities to enable today's advanced research solutions. As shown in Figure 10, ZEISS Xradia 515 Versa builds on the architecture, stability, and reputation of the ZEISS Xradia XRM platform with the latest resolution capabilities and modern software advancements. ZEISS Xradia 6XX Versa further build on the capabilities of ZEISS Xradia 515 Versa by accelerating scan throughput, improving reliability, and enhancing the user experience to deliver the highest performance next-generation X-ray microscope available in the market.

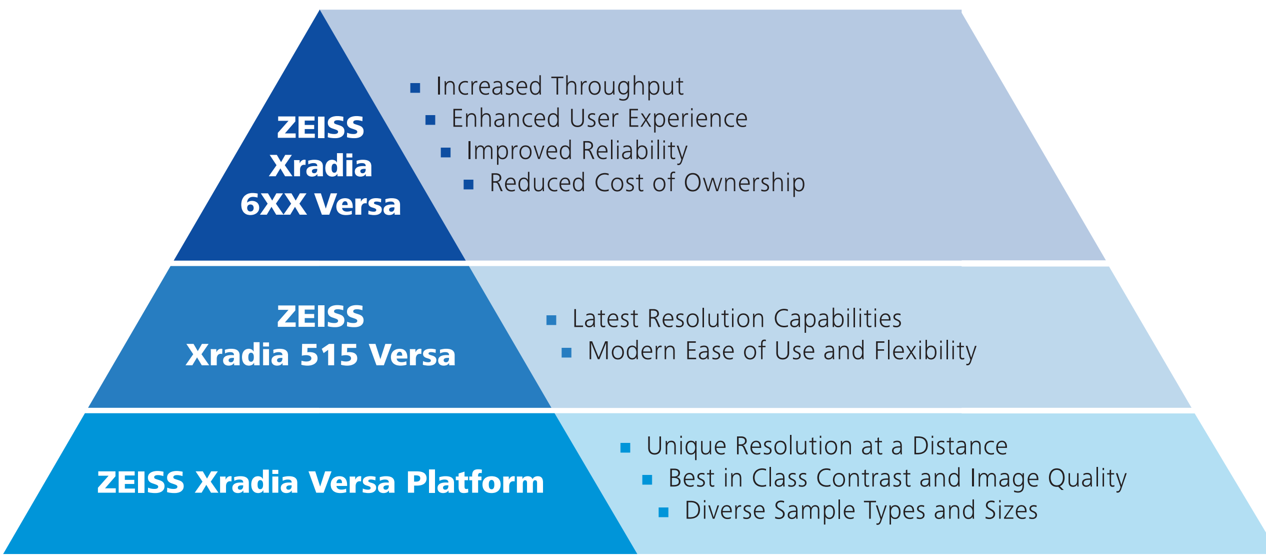


Figure 10 *A summary of the ZEISS Xradia Versa XRM family. The ZEISS Xradia Versa platform delivers RaaD capability, optimized contrast, and superior image quality across the widest range of sample types. ZEISS Xradia 515 Versa adds the latest resolution capabilities and modern ease of use and flexibility to this platform. ZEISS Xradia 6XX Versa further adds increased throughput, enhanced user experience, improved reliability, and reduced cost of ownership to these capabilities as the highest performance, next generation 3D X-ray microscope.*

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